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An ultra compactmulti mode interference coupler with parabolic down tapered geometry

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Abstract

A 2x2 multimode interference structure with parabolic down tapering has been proposed and realized by using silica waveguides with silicon oxinitride (SiON) core for the reduction of coupling length. The coupling behavior and dependence of fabrication tolerances on power imbalance of the proposed tapered structure have been compared with those of other tapered MMI structures having both down and up tapering by using a mathematical model based on sinusoidal modes. It has been found both theoretically and experimentally that the beat length (L_π) of the proposed tapered MMI coupler with Δn=5% is ~ half that of conventional MMI coupler and the deviation of power imbalance from its minimum value with fabrication tolerances ($\pm\ \partial w$ values) for the proposed tapered structure is more than that of other tapered structures.

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Keywords: Integrated optics;Parabolic taper; MMI; Power imbalance.

1. Introduction

Nowadays, Multimode interference (MMI) couplers have drawn attention in high density integrated optical devices of all optical networks and array based optical sensors, due to their properties such as compactness, high tolerances to the fabrication parameters, polarization insensitiveness etc. The basic components of these circuits based MMI couplers are 3dB coupler, power divider, modulator etc. The properties of these components are fully dependent on coupling characteristics of the MMI couplers and these characteristics are crucial to the performance of large scale integrated optical devices. The MMI couplers have been studied by many authors [1-7] and there

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also has been significant effort in understanding of their different tapered structures [4-6] for the reduction of its size. Although parabolic taper (both down and up) [4] and linear taper (both down and up) [5] provide the reduction of coupling length for MMI couplers based on general interference by ~ 40% and ~ 30% respectively, the fabrication tolerance of these tapered structures [4-5] is lower than that of a conventional structure. Compact and ultra compact MMI couplers with high index contrast varying from 2% to 16% have been fabricated by using InP / GaAsInP [1-2]and silica (SiO_2) /silicon oxinitride (SiON) [7-9]. Although SOI material provides high index contrast waveguides, SOI waveguides have higher propagation loss (~ 3dB/cm) [10] and higher fiber to chip loss (~ 2-3 dB/ facet) [10] than those of SiO_2/SiON [7] and InP /GaAsInP materials [11]. The SiO_2/ SiON material has become potential waveguide material because of its lower material cost in comparison to InP /GaAsInP. We have already shown [9] that for Δn=5%, the coupling length of the waveguide decreases slowly with increase of Δn.

In this paper, a new parabolic tapered MMI structure based on general interference has been proposed and realized by using silica waveguides with SiON core. The coupling characteristics and dependence of fabrication tolerances on power imbalance of the proposed MMI structure have been compared with other tapered MMI couplers [4-5].

Nomenclature

W_c	Cladding thickness
w	Width of access waveguide
h	Gap between two single mode input access waveguides
Δw	Gap between two output single mode access waveguides
p	Parabolic parameter

Greek symbols

β_0	propagation constant of first order
β_i	propagation constant of second order

2. Proposed parabolic down tapered structure

Several theoretical studies of conventional MMI couplers have been made [3-6], [8]. In a conventional MMI structure, more than two modes are excited at the input and the field transferred to the output access waveguide is contributed by all the modes excited inside the MMI waveguide. The overall effect is degradation in the coupling efficiency, as the power of higher order modes are transferred partly. To remove these excited higher order modes, a new parabolic tapered 2x2 MMI structure has been proposed, as shown in Fig-1(a).

In the figure, the width of input portion of MMI region is w_{mmi}= 2w+h whereas that of the output portion is w_0 = 2w+Δw (where w is width of access waveguides, h is gap between two single mode input access waveguides and Δw is gap between two output single mode access waveguides). The refractive index of core and surrounding cladding layers are n_1 and n_2 respectively. The input power P_1 is incident in the lower most input waveguide when the output powers P_4 and P_3 are obtained as a cross state and bar state, respectively. The principle of tapering can be understood in terms of reflection of plane wave fronts of propagation modes. Due to parabolic down tapering, the incident angle decreases at each reflection on the core-cladding interface. Since the angle of incidence for higher order modes becomes smaller than the critical angle, these higher order modes are refracted out from the MMI waveguide. Fig-1(b) shows a 2D representation of 2x2 parabolic tapered MMI coupler with access waveguides in which the origin is at left of MMI coupling region. As the lateral dimensions (along x-axis) in MMI region are ~ four times larger than the transverse dimensions (along y-axis), the waveguide structure is assumed to be of single mode in transverse direction and has same transverse behavior everywhere in the MMI region. So the coupling behavior of the MMI couplers can be analyzed by using two dimensional structures in which lateral (x-axis) and longitudinal characteristics (z-axis) are considered. Fig-1(c) shows the cross section view (AB) of proposed tapered MMI waveguide of cladding thickness W_c and over cladding thickness W_{oc}. The material for wave guide core, cladding and substrate are SiON, SiO_2 and silicon respectively.

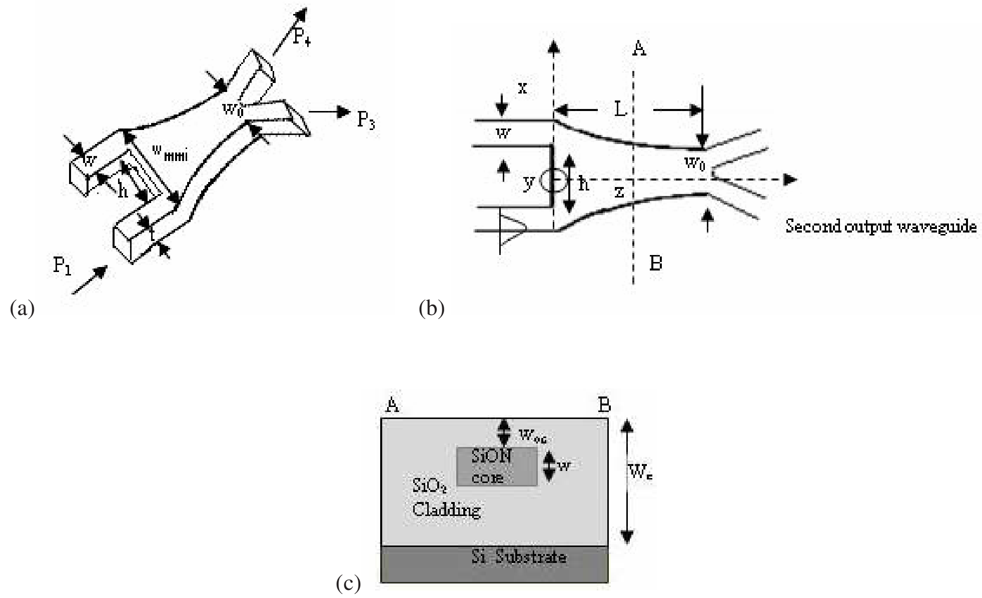

Fig. 1.Proposed tapered 2x2 MMI coupler of coupling length L with width 2w+h at input end and 2w+Δw at the output end(a) 3D view (b) 2D tapered structure containing x and z axis (c) Cross sectional view AB of Tapered MMI section.

The width of tapered region along z axis is written as,

$$w(z) = w_{mmi}[1 - 2(1 - p)\frac{z}{L}(1 - \frac{z}{2L})] \quad (1)$$

where, p $= w_0/w_{mmi}$= parabolic parameter. The input field profile H(x, 0), composed of mode field of all modes excited in MMI coupler is represented in two dimensional approximation as follows,

$$H(x,0) = \sum_{i=0}^{m-1} b_i^T H_i(x) \quad (2)$$

where, b_i^T = i^{th} mode field excitation coefficient, determined from Fourier series coefficients of odd periodic functions. $H_i(x)$ is mode field of i^{th} mode of MMI region at z =0. Themode excitation coefficients are Fourier series coefficients of odd periodic functions. This function for $0<x<w_{mmi}/2$ is constructed with $H(x,0)$ and -$H(-x,0)$ for $-w_{mmi}/2<x<0$. $H_i(x,0)$ is mode field of i^{th} mode of MMI region at z =0. The optical power is either transferred to the output waveguide or lost out at the end of multimode waveguide. Again the mode field at the output access waveguides of width, w is assumed to be mode 0. Since, each excited mode of the MMI coupler contributes to the mode 0 at the output access waveguide, the mode field of the output waveguide is the sum of the contribution of all the modes guided in MMI section and can be written for 1st and 2nd output waveguide as

$$H_1(x,L) = \sum_{i=0}^{m-1} c_{1,i}^T H_i(x) \exp[j(\beta_0 - \beta_i)L] \quad (3)$$

$$H_2(x,L) = \sum_{i=0}^{m-1} c_{2,i}^T H_i(x) \exp[j(\beta_0 - \beta_i)L] \quad (4)$$

Where β_0 and β_i are propagation constants of fundamental mode and i^{th} mode respectively. $c_{1,i}^T$ and $c_{2,i}^T$ are coefficient of field contribution of i^{th} mode for 1st and 2nd output waveguide of i^{th} mode for first and second output waveguides respectively, determined by using simple model based on sinusoidal modes [9]. The normalized power transferred to first and second output access waveguide is written as,

$$\left.\begin{aligned} \frac{P_3}{P_1} &= \left|\frac{H_1(x,L)}{H(x,0)}\right|^2 \\ \frac{P_4}{P_1} &= \left|\frac{H_2(x,L)}{H(x,0)}\right|^2 \quad (5) \end{aligned}\right\}$$

The normalized cross state (P_4/P_1) and bar state (P_3/P_1) coupling power versus coupling length for TE polarization of proposed parabolic (p=0.53) structure, with wavelength~1.55μm, w =1.5 μm, h =3μm, W_{oc} = 1.5 μm, W_c= 6 μm, cladding index~ 1.45 and Δn~5% estimated by using the equation (1)-(5), is shown by dotted lines in Fig-2(a).

The solid lines and dashed lines indicate the normalized coupled power distribution estimated by using the equations (2)-(5) with the same wavelength and index contrast for conventional structure (h = Δw = 3 μm) and the previously reported MMI structures having both parabolic down and up tapering (p=0.53) [4] respectively. The figure also shows the light wave propagation of all MMI structures obtained by BPM CAD software, OptiBPMversion 9.0 (mentioned in the figure), almost matching with the simulated results obtained by using simple model based on sinusoidal modes. It is evident from the figure that the beat length L_π for previously reported structure having both down and up tapering and proposed structure having only down tapering is 43.6 μm and 37 μm which provide 40% and 50% reduction of coupling length respectively in comparison to its conventional structure [1].This is because in tapered structures, the powers of higher order modes are refracted out at down tapered surface of MMI region as discussed earlier. But in case of the previously reported tapered structure [4], due to the presence of up tapering after down tapering, higher order modes are excited again. As the power of higher order modes are transferred partly, there is a degradation of coupling efficiency and as a result, the coupling length of the previously reported tapered structure is more than that of the proposed structure. In case of the proposed structure, the number of modes excited at z= 0 μm is eight and the number of modes at z=37μm (p=0.53) is three whereas in case of previously used tapered structure [4], the number of modes at input and output are eight and seven respectively.

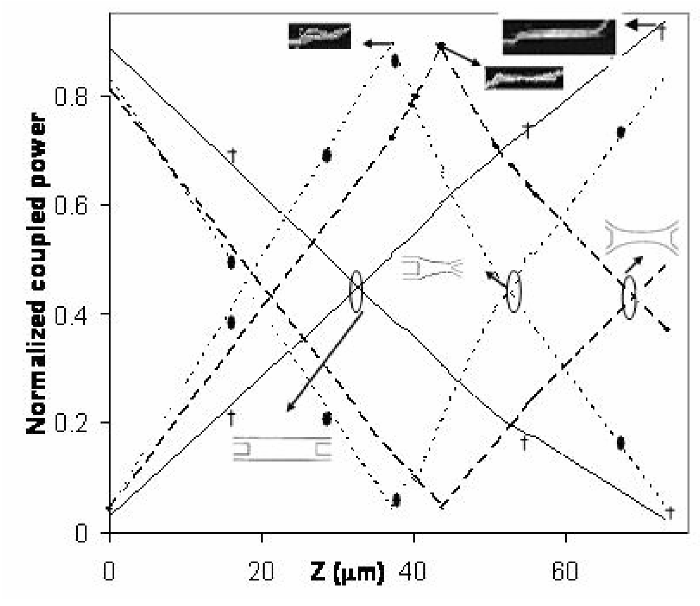

Fig. 2 (a).Coupling power distribution of proposed tapered and previously reported tapered and conventional MMI couplers with w_{mmi} ~6µm, w =1.5µm, cladding index~ 1.45, Δn~5%, wavelength ~1.55µm, (●)- experimental point of proposed tapered structure, (+)- experimental point of conventional structure).

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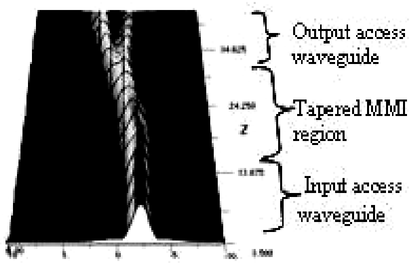
Table-1 shows the normalized power of different excited modes at input of MMI region and the power contributed by these modes to the first output access waveguide for the proposed tapered structure and the previously reported structure [4]. It is observed in the table that the normalized cross state power without bending loss contributed by all the modes present at z=37 µm for the proposed tapered structure and the previously reported tapered structure are estimated by using (3)-(5), as ~ 0.91 and 0.7098 respectively. This is due to less power contributed by different modes for the previously reported tapered structure than that for the proposed structure at z=37 µm. It is evident from the table that the maximum normalized cross state power without bending loss at z =44 µm for the previously reported tapered structure is 0.912. It has also been observed (not shown in the table) that the beat length (L_π) difference between TE and TM mode is obtained as 0.26% for both the tapered structures whereas, the beat length difference of TE and TM polarization for the conventional structure[1]-[6] is obtained as 0.25%. Hence the tapered structures are also polarization insensitive.

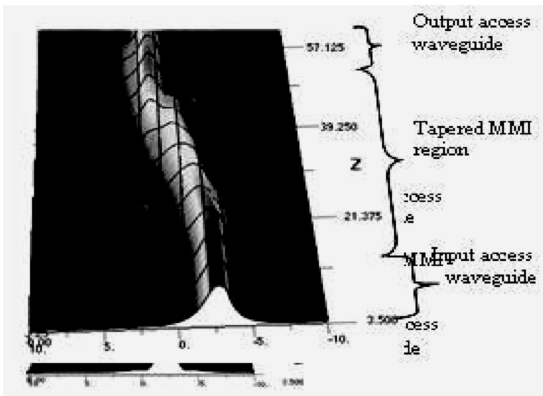
It is also evident from the figure that the peak coupling power in proposed structures having only down tapering is more than that of the parabolic tapered structure (having both down and up tapering) demonstrated by previous authors [4]. This is due to radiation loss (~ 0.027dB) at bent portion of both input and output access waveguides in the parabolic tapered structure demonstrated by previous authors [4] whereas in case of proposed tapered structure, it is due to radiation loss (~0.013 dB) at the bent portion of output access waveguide. The cross and black dots (discussed later in the paper) represent the experimental points for conventional and proposed structure respectively. Fig-2(b) shows the mode field propagation (obtained with OptiBPM software version 9.0) of wavelength 1.55µm in tapered MMI coupler of 3 dB coupling length 18.5 µm, proving 3 dB coupling at two output access waveguides. Fig-2(c) shows the mode field propagation (obtained with OptiBPM software version 9.0) of wavelength 1.55μm in tapered MMI coupler of coupling length 37 μm, proving cross coupling power at first output access waveguide(as shown in Fig-1).The L_π for p values varying from 0.4 to 1 obtained by using coupled power distribution curves with w =1.5 μm, cladding index~ 1.45 and Δn~5% at h ~2μm, 3μm and 4μm are shown in Fig-3.

Table 1.Power of different modes of TM polarization excited in proposed tapered MMI structure and MMI structure reported by previous authors [11] with Δn =5% and w_{mmi} =6 μm (h=3μm), p=0.53.

Mode number	Normalized power carried by different modes excited at z=0	Power contributed to crossed output access waveguide by different modes for tapered structure [11] at z =L_π=44 μm	Power contributed to crossed output access waveguide by different modes for the proposed tapered structure (at z=L_π=37μm).
0	~0.835	~ 0.982	~0.988
1	~0.08	~0.942	~0.983
2	~0.01	~0.93	~0.95
3	~0.002	~0.92	--
4	~0.001	~0.91	--
5	~0.0005	~0.905	--
6	~0.0003	~0.9	--
7	~0.0001	--	--



(b)



(c)

Fig. 2. (b) Lightwavepropagation of wavelength 1.55μm, for proposed tapered MMI coupler of 3 dB coupling length of 18.5 μm. (c)Light wavepropagation of wavelength 1.55μm, for proposed tapered MMI coupler of length of 37 μm.

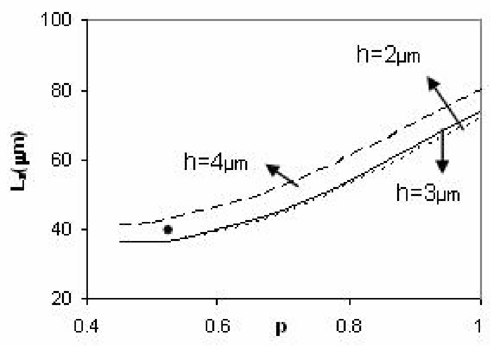


Fig. 3.Beat length versus p for different h values with cladding index ~1.45, index contrast~5%, wavelength~1.55µm and w ~ 1.5 µm.(●)- experimental point of proposed 3dB tapered MMI structure.

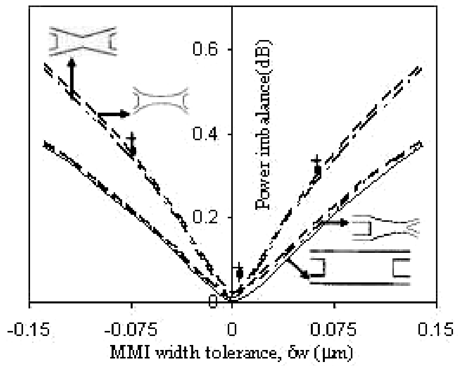


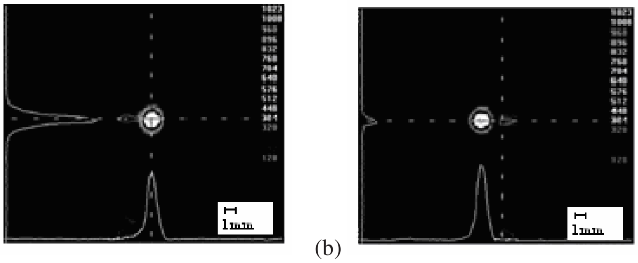
Fig. 4.Power imbalance characteristics versus MMI width tolerance (∂w) for conventional, proposed tapered, parabolic tapered and linearly tapered (at the middle) 3dB MMI coupler with cladding index ~1.45, h ~3µm, index contrast~5% power and w ~ 1.5 µm, wavelength~1.55µm and p~0.53. (●) - experimental point of proposed 3dB tapered MMI structure, (+)- experimental point of conventional 3dB MMI coupler.

In the figure, p=1 corresponds to the conventional MMI structure. It is evident that the beat length decreases with reduction of p and it is almost constant at p~0.53 for all mentioned values of h. As hdecreases, the curves become closer and closer and for h=3 µm the curve is almost close to h=2µm. So we have chosen p=0.53 and h =3 µm and the beat length obtained at p~ 0.53 and h =3µm is ~ 37 µm. The black dot in the figure represents the experimental point for p~0.53 and h =3 µm, matching well with theoretical curve. As it is difficult to fabricate the device with exact designed parameters, its performance degradation with these unwanted deviations of waveguide parameters during fabrication need to be studied.

Fig-4 shows the variation of power imbalance (=$10\log_{10}(P_3/P_4)$) with fabrication tolerance (± ∂w) of MMI width obtained by using the equations (3) with w~1.5 µm, index contrast ~5% and cladding index ~1.45 for the parabolic tapered structure (reported previously [4]) (p~ 0.53) of 3dB coupling length, $L_{\pi/2}$ ~21.8µm, linear tapered structure (reported previously [5]) of $L_{\pi/2}$ ~25 µm, the proposed tapered structure (p~0.53) of $L_{\pi/2}$ ~18.5 µm and conventional MMI structure of $L_{\pi/2}$ ~36.5µm. In all cases, minimum value of power imbalance is obtained at ∂w=0. The power imbalance increases with ± ∂w values almost symmetrically for all the structures. The figure shows that the curve of power imbalance in the proposed tapered structure is almost identical to that of the conventional structure whereas the deviation of power imbalance from its minimum value with ± ∂w values in case of reported structures (having both down and up tapering) demonstrated by previous authors [4-5]is more than that of the proposed MMI structure. The cross and black dots in the figure represent experimental points of conventional and proposed tapered structures with p~0.53 respectively, matching well with theoretical curves.

3. Realization of proposed tapered structure

The proposed parabolic tapered MMI couplers of different coupling lengths with p~0.53 and h=3μm were fabricated by using SiO_2/SiON material with Δn =5%. On silicon substrate, embedded waveguide including MMI section and access waveguides of core width w=1.5μm were made by plasma enhanced chemical vapour deposition (PECVD), photolithography and reactive ion etching (RIE). The conventional MMI couplers of different coupling lengths were also fabricated by using SiO_2/SiON material with Δn =5% for comparison. The coupling powers of both the proposed structure and conventional structure were measured with a stabilized laser diode of wavelength 1.55 µm and germanium p-i-n detector at the other end through the focusing lens. The output field of first output waveguide and second waveguide were monitored by an infrared CCD situated at distance 10 mm from the waveguide.



(a) (b)

Fig. 5. Output fields obtained by an infrared CCD situated at 10 mm from waveguides (a) at first output waveguide and b) at Second output waveguide.

Fig-5 shows the beam spots first and second output waveguide, proving single mode output. The diameters of beam spots of first and second output waveguide are ~ 2.7 mm and ~ 2.63 mm respectively. For the measurement of waveguide propagation loss and fiber to chip loss, single mode straight waveguides (w=1.5µm) of length of 50 µm and 10,000 µm were fabricated by using SiO_2/ SiON material. The chip to fiber loss was measured with 50 µm straight waveguide by considering negligible propagation loss in comparison to chip to fiber loss due to smaller length and taking back ground power which was measured by moving detector with 10 µm distance in both sides of exact alignment position. The measurement of the propagation loss was made with 10,000 µm straight waveguide bydeducting chip to fiber loss from total measured loss. The wave guide propagation loss was ~0.15 dB/cm and the fiber to chip loss per facet was < 1.2 dB. The measured values of normalized coupling power for tapered and conventional MMI structures match closely with theoretical curves in Fig-2(a). It was observed that the beat length (L_π) of tapered MMI structure of p~0.53 is ~half that of the conventional MMI structure.

4. Conclusion

A novel parabolic down tapered structure of MMI coupler has been proposed and realized by using SiO_2/SiON materials for high speed communication and instrumentation. It has been found both theoretically and experimentally that the beat length (L_π) of the proposed MMI coupler with Δn=5% and p~0.53 is reduced by ~50% of that of conventional MMI couplers. It has also been observed that the deviation of power imbalance from its minimum value with ± ∂w values is almost same for the proposed structure and conventional structure whereas that for other tapered structures having both down and up tapering is more than that of the proposed structure.

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